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Seasonal variations of solar neutrino rates in lithium detector

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Abstract

The presence of two monochromatic lines of approximately equal intensity: ^{7}Be- and pep-neutrinos in the sensitivity plot of lithium detector makes the pattern of the seasonal variations of the effect from solar neutrinos very characteristic in case if the long-wave vacuum oscillations are realized. This can give the very high accuracy in the measurement of the parameters of neutrino oscillations especially if combined with the results obtained by the detector sensitive mainly to ^{7}Be-line like BOREXINO or KamLAND.

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Keywords: Solar neutrinos; Neutrino oscillations; Seasonal variations

The recent results obtained by the SNO detector [1] compared with the previous results of SuperKamiokande [2] have shown that in the flux of solar neutrinos only approximately $1/3$ are the electron neutrinos while the rest $2/3$ are the μ-, τ-neutrinos which proves that neutrinos do oscillate. This result albeit needs further confirmation may have a dramatic influence on the neutrino physics in general and on the neutrino astrophysics in particular. The important issue of this is the determination with the highest possible accuracy the parameters of neutrino oscillations. Which way the further development will take depends critically on Δm^2 realized in the solar neutrino data. If LMA region with Δm^2 of about 10^{-5}–10^{-4} eV^2 is the solution this will open great field of research for neutrino factories with the real perspectives to observe CP- and T-violations in neutrino oscillations [3]. But if the long-wave vacuum oscillations are the choice of nature then there will be a good opportunity to observe the seasonal variations in solar neutrino detectors. This possibility looks attractive both for electronic [4] and for radiochemical [5] detectors, the only crucial thing is the accuracy of measurements. It will be shown in this Letter that lithium radiochemical experiment is able to furnish the valuable information on this subject and that the combination of the results of lithium detector with the results of the one sensitive mainly to ^{7}Be neutrinos like BOREXINO [6] or KamLAND [7] will enable to fix parameters of neutrino oscillations with very high accuracy.

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Recently the new results were obtained by SNO Collaboration [8]. The combined global analysis of data of all solar neutrino experiments indicate that the best fit of the data is provided by the LMA MSW solution [9]. If this is confirmed by future experiments, the characteristic modulation discussed here will not be seen. But the VAC solution is still present at 3σ level [9]. To establish this point the very decisive results are expected from KamLAND [7].

The lithium detector was proposed by Bahcall [10] and is utilizing the reaction of neutrino back capture on lithium with the threshold of 0.86 MeV for the ground state to ground state transition:

$$^{7}\mathrm{Li} + \nu \to {}^{7}\mathrm{Be} + \mathrm{e}^{-}.$$

The ground-state to excited-state transition

$$^{7}\mathrm{Li} + \nu \to {}^{7}\mathrm{Be}^{*} + \mathrm{e}^{-},$$

with the energy of the excited state 0.478 keV contributes about 10% to the total effect from solar neutrinos. The cross-section of this reaction is relatively high and can be computed with very high accuracy because both transitions are superallowed [11]. Another advantage of lithium target is that in the sensitivity plot, as one can see on Fig. 1, two monochromatic lines: ^{7}Be and pep are of approximately the same amplitude, see also Table 1 taken from [12]. We neglect here the contributions from hep- and ^{17}F-neutrinos.

These attractive features of lithium detector were the reason why since the early phase of solar neutrino

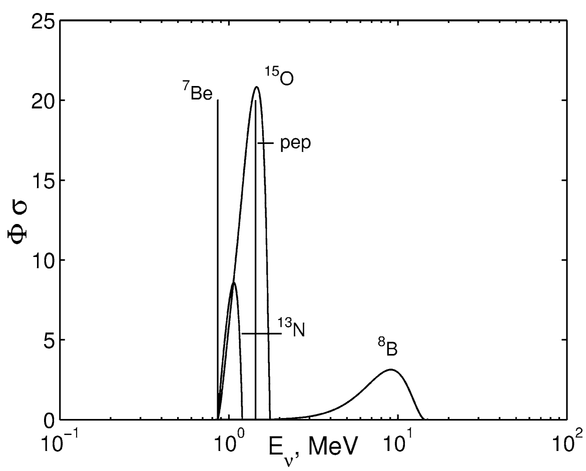

Fig. 1. The sensitivity plot of lithium detector.

research lithium detector was considered as an important element of the program of the full neutrino spectroscopy of the Sun [13,14]. Two monochromatic lines of approximately equal intensity is a unique case for lithium target. The flux of pep-neutrinos from the Sun is approximately 35 times lower than the flux of ^{7}Be-neutrinos [12]. So any detector sensitive to both lines will see the effect from pep-line as a small admixture to the one from very intensive line of ^{7}Be-neutrinos. But this is not true for the lithium detector. It happens because in the laboratory conditions the ^{7}Be line will not produce ^{7}Be on lithium since the reaction of ^{7}Be production is reverse to electron capture by ^{7}Be. If to consider electron screening in terrestrial atoms, the energy of ^{7}Be line is even lower than a threshold for ^{7}Be production. But in the Sun high temperature produces the thermal broadening of the ^{7}Be line, as it was first understood by Domogatsky [15] and later was computed with high accuracy by Bahcall [16]. Because of this some fraction of the line with the energy higher than the threshold will produce ^{7}Be and the calculations show [12] that the yield of ^{7}Be by this channel is almost equal to the yield by pep-neutrinos as one can see from Table 1. If the long-wave vacuum oscillations are realized which is one of the probable solutions by the presently available data [17–22] than the pattern of the seasonal variations in lithium detector will be very characteristic, which can be used both for the needs of the full-spectroscopy of solar neutrinos and for the determination of the parameters of neutrino oscillations as it was proposed in [5].

The general idea of using the seasonal variations is based on the connection of the shape of the curve of the seasonal variations with the oscillation parameters. The variation of the effect for a monochromatic source in case of vacuum oscillations is described by the following expression:

$$\begin{aligned} R(E,t) &= \Phi\sigma(E)(1 - 2\varepsilon\cos\pi t) \\ &\quad \times\left[1 - \sin^2 2\theta \sin^2\left(1.9\times 10^{11}\Delta m^2 r(t)/E\right)\right]. \end{aligned} \tag{1}$$

Here Φ is the flux of neutrinos calculated for the distance Sun–Earth 1 a.u., $\sigma(E)$ is the neutrino capture cross-section, the value $\Phi\sigma$ is measured in SNU (1 SNU is the capture rate per second in 10^{36} atoms of the target), $\varepsilon = 0.0165$, $r(t) = 1 + \varepsilon\cos\pi t$, t varies

Table 1
The capture rates of solar neutrinos on chlorine, gallium and lithium according to solar model BP2000 [12] and to the results of SNO experiment [1,2] (for boron neutrinos)

Source	Flux (10^{10} $m^{-2}\,s^{-1}$)	Capture rate (SNU)		
		Chlorine	Gallium	Lithium
Pp	$5.95(\pm 1\%)$	–	69.7	–
Pep	$1.40 \times 10^{-2}(\pm 1.5\%)$	0.22	2.8	9.2
Hep	9.3×10^{-7}	0.04	0.1	0.1
^{7}Be	$4.77 \times 10^{-1}(\pm 10\%)$	1.15	34.2	9.1
^{8}B	$1.75 \times 10^{-4}(\pm 8\%)$	2.0	4.2	6.8
^{13}N	$5.48 \times 10^{-2}(+21/-17\%)$	0.09	3.4	2.3
^{15}O	$4.8 \times 10^{-2}(+25/-19\%)$	0.33	5.5	11.8
^{17}F	$5.63 \times 10^{-4}(\pm 25\%)$	0.0	0.1	0.1
Total		3.83	120	39.4

from 0 (aphelion) till 1 (perihelion), this corresponds to one half of a year, beginning from aphelion. The factor $\Phi\sigma(1 - 2\varepsilon \cos \pi t)$ describes the seasonal variations of $1/r^2$ which accounts for 3.3% modulation of the solar flux. For the continuous sources (^{13}N, ^{15}O, ^{8}B) the integral was taken:

$$R(t) = \int\limits_{E_{\rm TH}} \frac{\varphi(E)}{\Phi} R(E,t)\, dE, \qquad (2)$$

here $\varphi(E)$ is the flux of the neutrinos per energy interval dE, $E_{\rm TH} = 0.86$ MeV is the threshold of lithium detector. The values $\varphi(E)$ and $\sigma(E)$ were taken from [23]. It was shown in [24] that the magnitude of the modulation of the effect is critically dependent on Δm^2 for all neutrino sources on the Sun what can be efficiently used in experiment.

The curves of the expected seasonal variations in lithium detector were calculated for two sets of Δm^2 and $\sin^2 2\theta$: one of 1.4×10^{-10} eV^2 and $\sin^2 2\theta = 0.8$ corresponds to the best fit point of the global solutions in the free flux analysis and another one of 4.8×10^{-10} eV^2 and $\sin^2 2\theta = 0.9$ corresponds to the best fit point of the global solutions in the SSM restricted flux analysis [20]. They differ drastically as one can see from Fig. 2. So these two solutions can be well resolved by lithium detector. The evaluated mass of the lithium target adequate to perform the high precision measurements of the seasonal variations is 100 tons. Then the accuracy of each one-month point will be about 2.5% for 4 years of experiment if to measure the ^{7}Be activity by means of a cryogenic microcalorimeter [25,26].

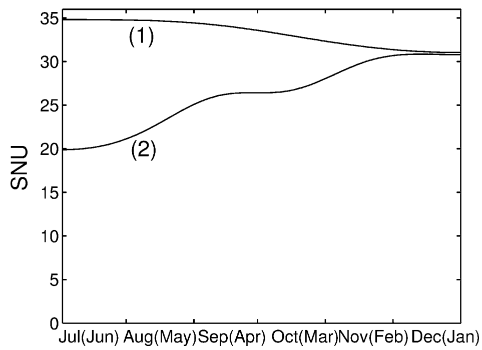

Fig. 2. The seasonal variations of the effect in lithium detector for $\Delta m^2 = 1.4 \times 10^{-10}$ eV^2, $\sin^2 2\theta = 0.8$ (1) and $\Delta m^2 = 4.8 \times 10^{-10}$ eV^2, $\sin^2 2\theta = 0.9$ (2).

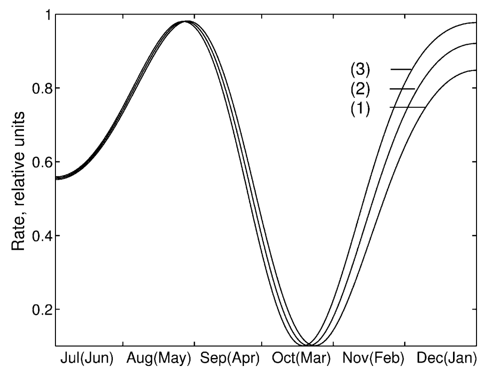

Fig. 3. The seasonal variations for ^{7}Be line for $\Delta m^2 = 4.66 \times 10^{-10}$ eV^2 (1), $\Delta m^2 = 4.8 \times 10^{-10}$ eV^2 (2) and $\Delta m^2 = 4.94 \times 10^{-10}$ eV^2 (3).

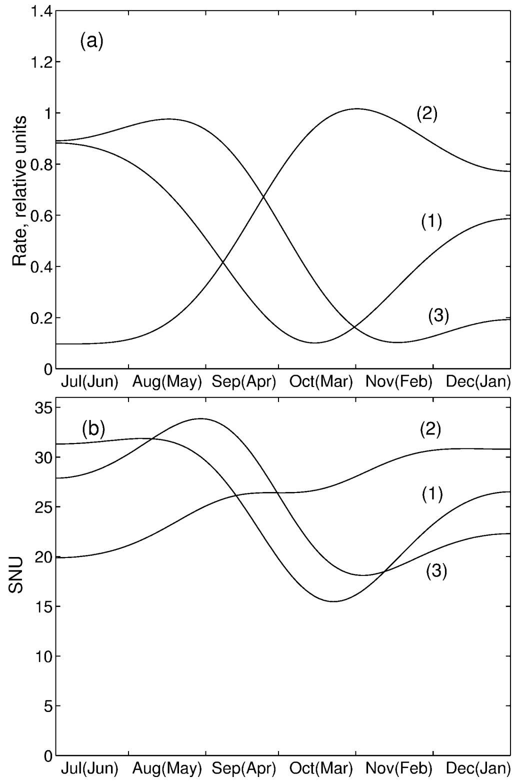

Fig. 4. The seasonal variations for pep-line (a) and of the effect in lithium detector (b) $\Delta m^2 = 4.66 \times 10^{-10}$ eV^2 (1), $\Delta m^2 = 4.8 \times 10^{-10}$ eV^2 (2) and $\Delta m^2 = 4.94 \times 10^{-10}$ eV^2 (3).

The shape of the curve of the seasonal variations is modified with the energy of neutrinos detected in experiment. The overlap of the allowed regions obtained by lithium detector and by the one sensitive only to ^{7}Be line will enable to reach higher accuracy. If to take, for example, three adjacent values of Δm^2 on Fig. 2 (Ref. [24]) which have the same annual average and which are close to 4.8×10^{-10} eV^2 then the shapes of the seasonal curves for the detector sensitive only to ^{7}Be neutrinos will be very alike as one can see from Fig. 3. In experiment it may be difficult to find what is the true value of Δm^2 because the accuracy of the measurements may be not sufficient to make the reliable selection between these alternatives.

For the detector sensitive to other line, pep-line, the shapes of the curves for the same three values of Δm^2 will be very different as one can see from Fig. 4(a). It would be much easier in this case to discriminate between these three cases.

The conclusion is that the comparison of the seasonal variations obtained by ^{7}Be-detector and pep-detector will enable to find the Δm^2 with the very high accuracy. The lithium detector is sensitive to several sources of neutrinos, this creates some smearing effect. But still, the presence of two monochromatic lines of high and approximately equal intensity makes this detector very efficient in providing the independent information to determine Δm^2. Fig. 4(b) shows the curves for lithium detector for the same values of Δm^2. One can see the big difference of the shapes that can be efficiently used for finding what is the true value of Δm^2.

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